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WET EXPANSION ENGINE FOR HELIUM REFRIGERATOR APPLICATION

PREPARED UNDER FERMILAB SUBCONTRACT NO. 94199
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FOR

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I. INTRODUCTION

CCI Report No. 390-112 entitled, Investigation of Means to Increase Refrigeration Capacity of the CHL/Satellite Refrigeration System of the Fermilab Energy Doubler", indicates that wet engine efficiency is of extreme importance to the performance of the Fermilab energy doubler refrigeration system.

Wet engines, used to date, are reciprocating machines operating at speeds of 100 to 200 rpm. Efficiency of the machines is not known exactly, but appears to be in the range of 60-80%. The efficiency is quite sensitive to ratio of inlet displaced volume and temperature and pressure conditions of the fluid at the inlet of the engine. For this reason, efficiency may vary considerably for the same engine, dependent on mode of operation.

This report describes a concept of wet engine which, in principle, is independent of fluid conditions at the inlet and which appears to have the possibility of providing a thermodynamic efficiency in the range of 90-100% under widely varying operating conditions.

II. DESCRIPTION OF CONCEPT

Figure 1 shows the basic arrangement. The expander consists of a cylinder and piston with two valves admitting or venting gas from the space A below the piston and two valves admitting or venting gas from the space above the piston. The piston may be connected to a variable speed motor, capable of moving the piston at varying speeds. A typical cylinder will be 4 in. in diameter with a total stroke of 8 in. Displaced volume is then of the order of 100 cu in. (1,640 cc).

The expander operates as follows:

During the intake stroke, valves V1 and V3 are open and valves V2 and V4 closed. The space below the piston is connected to the high pressure circuit of the cold box of refrigerator or liquefier. The inlet valve V1 remains open until approximately 75-85% of the total stroke is completed.

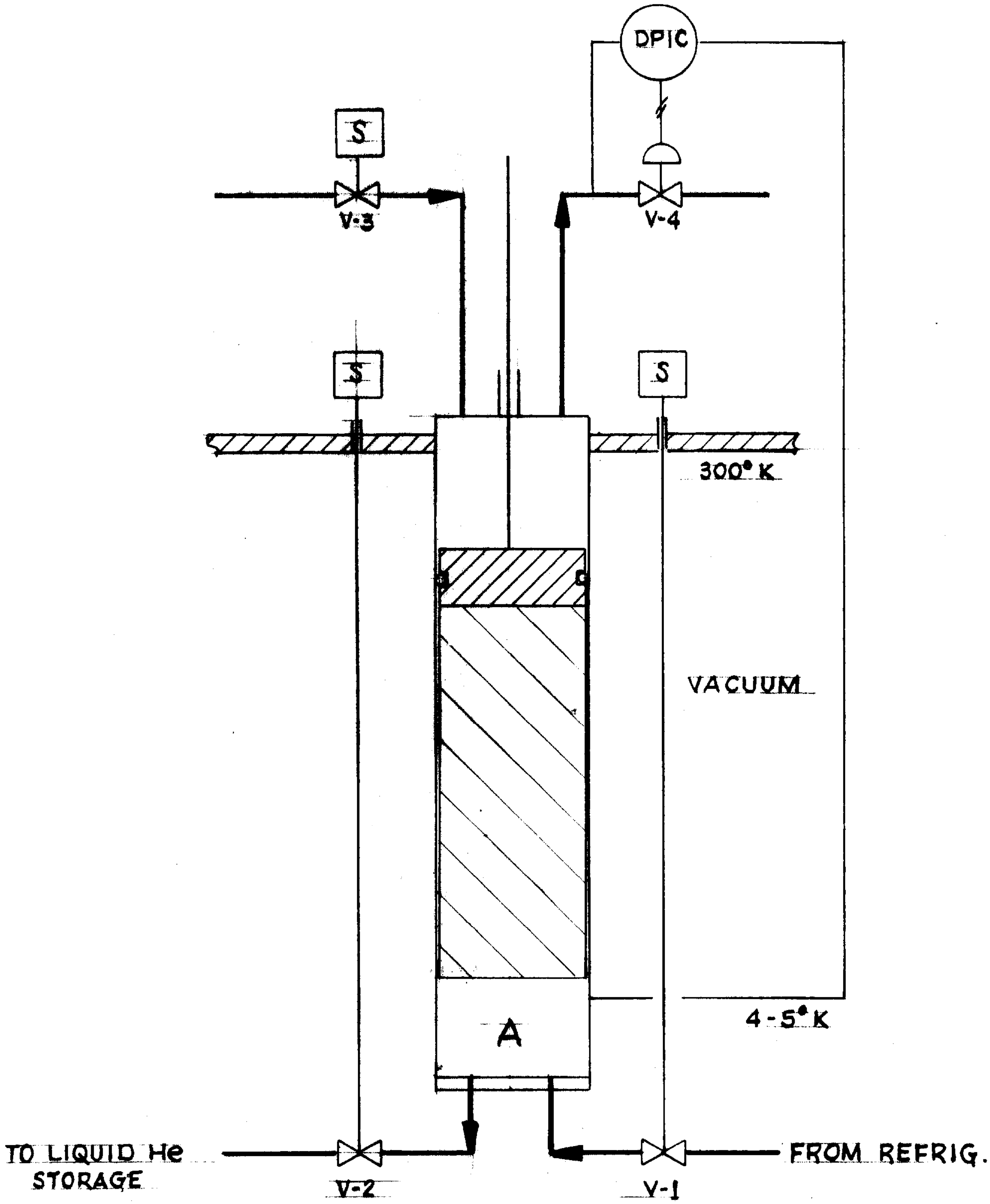
DPIC
S
V-3
V-4
S
S
300° K
VACUUM
A
4 - 5° K
TO LIQUID He
STORAGE
V-2
V-1
FROM REFRIG.

FIGURE - 1

Piston speed may be controlled by pressure in the cylinder or, if pressure is controlled in some other way, speed may be maintained at a constant level. After closure of valves V1 and V3, the piston continues to move, and the fluid in the cylinder expands to a pressure of 1.4 to 2.0 atm, dependent on discharge system conditions. Valve V4 is open during the expansion stroke. At the end of the stroke, valve V2 opens, and the piston is driven to the bottom of the cylinder. At that time, valves V1 and V3 open again, valve V2 closes, and the next cycle starts.

Some numbers are instructive. Assume a flow rate of 50 g/sec. Inlet conditions will be as follows:

Pressure:	20 ata
Temperature:	5.2°K
Enthalpy:	3,147
Entropy:	21.68 J/gr °K
Specific Volume:	6.348 cc/gr

Discharge conditions after a reversible ideal expansion will be:

Pressure:	1.8 ata
Temperature:	4.05°K
Enthalpy:	9.07 J/gr
Entropy:	3.147 J/gr °K
Specific Volume:	7.51 cc/gr

With the inlet and discharge conditions as specified, the 4 in. diameter cylinder will be filled with 219.4 gr of fluid at the end of the expansion stroke. The length of time during which the inlet valve is open is then 4.39 sec. Inlet valve closes, when 84.5% of the stroke has been carried out. By maintaining a constant piston speed, inlet and expansion cycle will take 5.2 sec.

The discharge stroke can be carried out fast and could last 2-3 sec. Total time of one cycle is then 7-8 sec, during which 219.4 gr of fluid have been processed. Average flow rate is then some 30 g/sec.

In order to make the operation continuous, two cylinders in parallel should be used. Operation of the cylinders relative to each other should then be as indicated in Figure 2.

Flow from the refrigerator cold box is continuous while discharge of fluid occurs during 37.5% of the time.

Efficiency of the Device

How reasonable is it to expect a high efficiency near 100%? Consider the losses in the engine:

a) Friction between Rings and the Wall:

When pressure is equal on both sides of the rings, it is not necessary to provide a ring of large area for sealing purposes. If the sealing ring has a width of 1/8 in. and the cylinders a diameter of 3-7/8 in., total travel of the piston under pressure is approximately 20 cm. Assume a friction coefficient of .1. Then total work put into frictional heat is:

$$\pi \times .1 \times .125 \times 3.875 \times 294 \times \frac{17.27}{30.5} = 25.33 \text{ ft-lbs}$$

$$= 35 \text{ joules}$$

During the return stroke, pressure in the cylinder is low and friction can be ignored.

b) Piston Ring Leakage:

With equal pressure on both sides of the ring, leakage should be zero. There may be some leakage during the expansion stroke when pressure difference across the ring may have a finite value. Leakage in or out of the cold volume yields the same loss, when the volume above the cylinder is maintained at ambient temperature. For each gram of gas transported between warm and cold volume an energy transfer of approximately 1,500 joules takes place. Since total cold production for a 4 sec intake of cold gas is approximately 2,500 joules, leakage from cold to warm volume or vice versa needs to be maintained at a very low value.

c) Heat Transfer between Walls of Cylinder and Fluid:

The effect in the cold cylinder is zero, because the wall of the cylinder has no heat capacity.

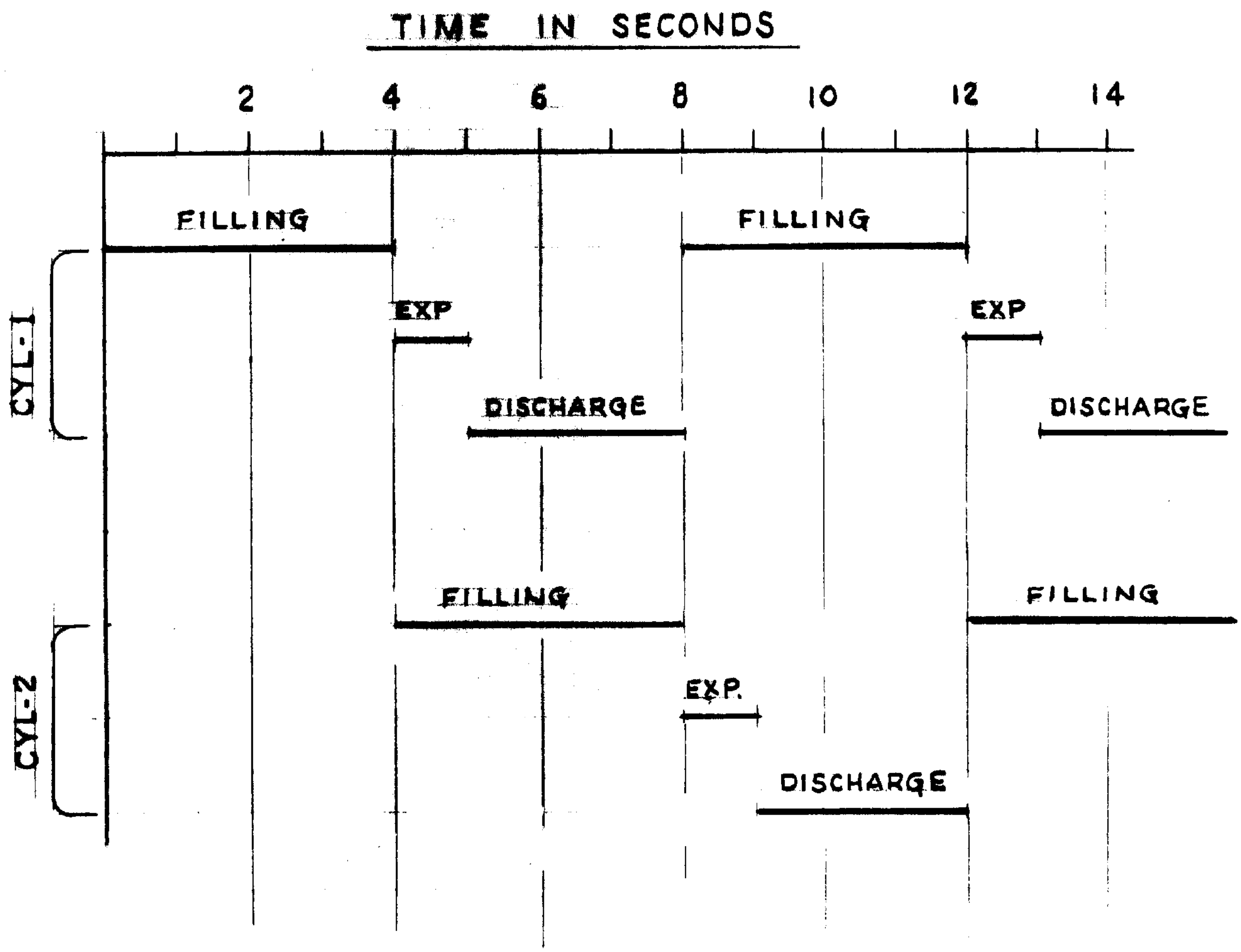
TIME IN SECONDS
2
4
6
8
10
12
14
FILLING
FILLING
CYL-1
EXP
EXP
DISCHARGE
DISCHARGE
FILLING
FILLING
CYL-2
EXP.
DISCHARGE

FIGURE - 2

d) Heat Leak from Warm to Cold End;

Conduction is through wall of cylinder and piston. The piston needs to be made of a non-metallic material or filled with helium gas under pressure and stratified. Conduction in a wall of .065 in. thickness, 4 in. in diameter, and 24 in. long temperature gradient is of the order of 2.7 watts or 22 joules for an 8 sec cycle. Conduction through a column of helium gas of 24 in. length and 3-7/8 in. diameter is of the order of milliwatts. Conduction through a cylinder made of G-10 or micarta will be of the order of .2 to .5 watts.

e) There will be some helium gas with a temperature gradient locate between cylinder and piston;

The mass contained between cylinder and piston is a function of piston clearance and length of section with temperature gradient. Gas moves in and out of this space. As soon as the cylinder is opened to the high pressure side of the satellite refrigerator, gas will be compressed. During expansion, this gas returns to the cold volume. There is some transport of heat associated with this. The amount can be estimated as follows:

Volume is .002 x π x 3.875 x 24 = .584 cu in. where .002 in. is radial clearance between piston and cylinder. Mass in volume at an average temperature of 100°K and 20 ata is .091 grams (V_s = 105.5 cc/gr). Mass in volume at low pressure (1.4 ata) and the same average temperature is .0065 grams (V_s = 1,467 cc/gr). Essentially, all the gas moves in and out of the cylinder. The worst condition in terms of heat transport would be a return of ambient temperature gas into the cylinder. Heat added to the cold cylinder is then 1,500 joules per gram or a total of 130 joules. It will not be this bad, because the wall and piston will act as a regenerator. This will reduce the heat transport by at least a factor 3 or 4.

f) Valve Leakage:

During the inlet stroke, leakage through the discharge valve will result in zero enthalpy change of the leaking fluid.

During the expansion stroke, inlet and discharge valve may leak. The effect of discharge valve leakage during this time is somewhat less, because the leaking fluid enthalpy is being reduced in the expansion process. The effect of inlet valve leakage during the expansion stroke is a loss of enthalpy drop ranging from zero at the start of the stroke to the full value of 12.7 joules per gram at the finish of the stroke. Gas leakage during the exhaust stroke represents a loss in enthalpy reduction of the leaking fluid. Roughly, loss in efficiency of the engine due to valve leakage is proportional to the fraction of fluid leaking through the valves.

g) Varying Inlet Conditions:

Typically, the inlet pressure will be a fixed value determined by refrigerator or liquefier compressor characteristics. The inlet temperature may vary widely. For instance, in a typical liquefier operation, inlet temperature may be 7.5°K, while a typical satellite operation will show 5.2 to 5.3°K. The effect of varying the ratio of total displaced volume to inlet volume is shown in Table I for liquefier operation:

TABLE I

In		Out			
P =	20 atm	P =	1.8	P = 2.0	P = 2.2
T =	7.5°K	T =	4.911	T = 5.032	T = 5.083
H =	30.52 J/gr	H =	15.52	H = 15.73	H = 15.94
S =	4.549 J/gr-°K	S =	4.549	S = 4.549	S = 4.549
V_{s_1} =	7.254 cc/gr	V_{s_2} =	11.03	V_{s_2} = 10.03	V_{s_2} = 9.39
		V_{s_2}/V_{s_3} =	1.52	= 1.38	= 1.294
		*R =	1,360	= 1,474	= 1,553

*R is the total refrigeration (joules) generated in a displaced volume of 1,000 cc.

The table shows that the refrigeration generated per unit mass does not change much when expanding to lower pressures.

Table II provides the data for the same expander operating with a low inlet temperature:

TABLE II

P =	20 atm	2.2	2.0	1.8	3.0
T =	5.2°K	4.06	4.04	4.02	4.14
H =	21.68 J/gr	9.39	9.23	9.08	10.0
S =	3.147 J/gr-°K	3.147	3.147	3.147	3.147
V_{s_1} =	6.348 cc/gr	V_{s_2} = 7.46	7.48	7.51	7.37
		V_{s_2}/V_{s_1} = 1.175	1.178	1.183	1.161
		R = 1,647	1,664	1,678	1,585

Adjustment to the varying inlet conditions can be made by sensing the pressure in the cylinder at the end of the expansion cycle and adjusting the cutoff point of the inlet stroke (closure of valve V1) accordingly.

Main contribution to inefficiency is piston ring leakage either from cold to warm volume or vice versa. To reduce the leakage, difference in pressure across the piston will be monitored, and the signal will be used to bleed gas from the warm volume during the inlet and expansion stroke.